SUBSURFACE GEOPHYSICAL IMAGING OF LAVA TUBES, LAVA BEDS NATIONAL MONUMENT, CA

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Abstract

The Central Federal Lands Highway Division (CFLHD), FHWA, located in Denver, CO, is primarily responsible for the rehabilitation, reconstruction, and repaving of National Forest and Park roads in the western states region. At many sites, such as the Lava Beds National Monument (LBNM) in northern California, there are concerns that unknown near-surface voids pose significant risks to roadway construction activities, the long-term stability and maintenance of the roadway, and to public safety. To help quantify issues related to unknown voids and determine suitable mitigation measures, CFLHD undertook a preliminary investigation into non-invasive geophysical methods aimed at **(1)** characterizing the presence and vertical/horizontal extent of voids, **(2)** determining the best geophysical methods for specifically conducting roadway surveys, and **(3)** identifying the range of applications nationwide. As a starting point to these more encompassing project goals, CFLHD contracted Blackhawk GeoServices, Golden, CO, to conduct a variety of geophysical surveys at LBNM to identify methods suitable for locating near-surface lava tubes prior to planned roadway construction within the Park.

Currently, several geophysical methods exist to locate subsurface voids. Each method has limitations in depth and resolution accuracy based on geological factors and void size, shape, and orientation. In order to define these limitations in a semi-controlled investigative setting, data were collected over known cave locations. The geophysical methods utilized at LBNM included magnetics, ground penetrating radar, high resolution shear wave reflection, and electrical resistivity.

This report contains general information about Lava Beds National Monument, survey site descriptions, an overview of the geophysical methods utilized, data acquisition parameters, processing steps, interpretations of each method, and a comparison of the utility and accuracy of the methods. This report will be of interest to contractors and construction crews conducting work in areas where subsurface voids may exist.

Introduction

Overview

This report contains the procedures and results of surface geophysical surveys performed at the Lava Beds National Monument (LBNM) located in Siskiyou County, California. Blackhawk GeoServices (Blackhawk) performed the fieldwork for the Central Federal Lands Highway Division (CFLHD), FHWA, in October 2003. The objective of the geophysical surveys is to determine the optimum geophysical technology for delineating lava tubes that may pose a threat to road construction crews and heavy equipment working above them. This report summarizes the geophysical techniques used at LBNM to locate subsurface voids as well as recommendations for future work.

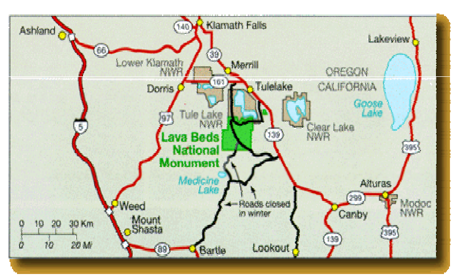

Figure 1 – LBNM location map

Site History

Lava Beds National Monument encompasses 73 square miles in northern California and is located approximately 50 miles

South of Klamath Falls, Oregon. The park contains over 460 lava tube caves from over 30 separate flows making it the largest concentration of lava tube caves in the continental United States. The Monument is located on the northeast side of Medicine Lake Volcano. Medicine Lake Volcano is a classic shield volcano that is about 500,000 years old. Its surface area covers over 700 square miles and it is the largest volcano in the Cascade Mountain Range.

Blackhawk conducted geophysical surveys at three locations (Golden Dome, Hercules Leg, and Indian Well Cave) in the vicinity of Cave Loop (Figure 2) in the southern end of the monument. One location (Monument Road Cave) along Hill Road near Devil's Homestead Flow was also investigated. LBNM officials have requested that Blackhawk not identify the exact location of the lava tube along Hill Road.

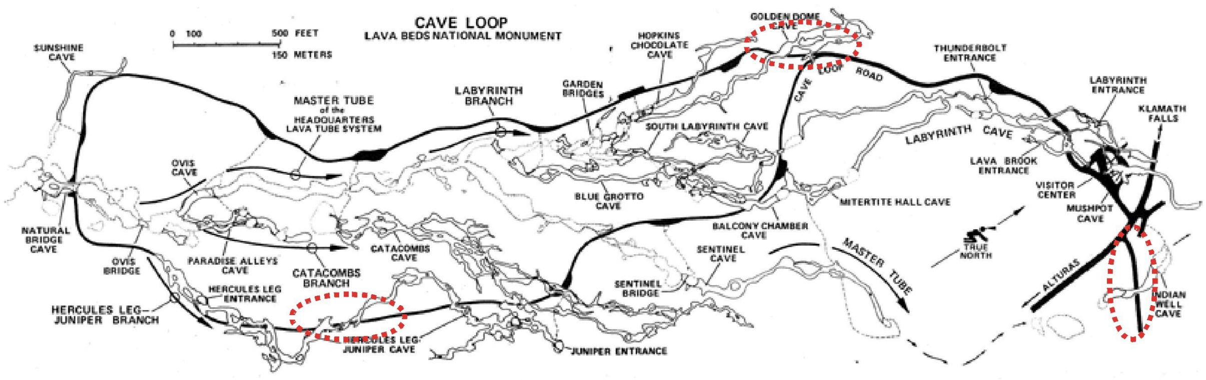

Figure 2 – Cave Loop site map with geophysical survey areas outlined in red (Larson et al, 1990)

Lava Tubes

J.D. Howard was one of the first to explore Lava Beds National Monument. According to Howard, in an accurate statement made well ahead of his time, "Pahoehoe lava is the only lava supporting caves. This type freezes on the surface the same as water, or rivers, but as the lava has no continuous supply, it runs out underneath the capping. In the ravines or at deep places it leaves tubes… in places the crust breaks down leaving tube openings" (Larson et al, 1990).

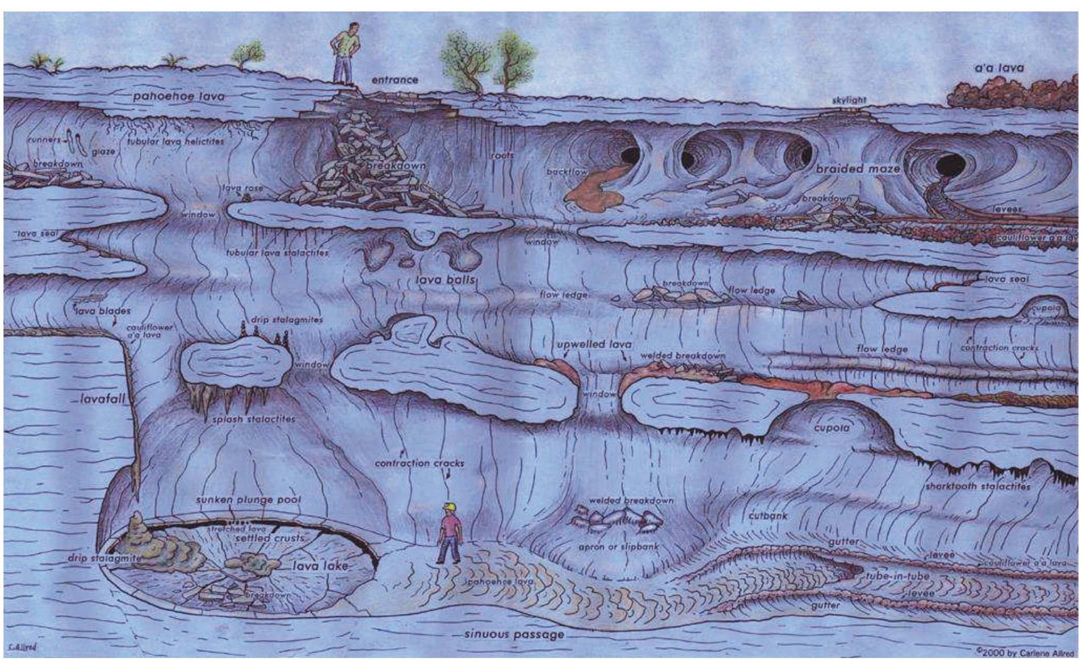

Figure 3 – Various lava tube features – picture from "The Virtual Lava Tube" [http://www.goodearthgraphics.com/virual_tube/virtub.html]

There are two different types of lava tubes. First, surface tubes are created when the top and sides of the lava flow cool due to their exposure to the air. This cooled lava solidifies creating a hard cast surrounding the flowing lava. They are usually covered by the oncoming flow. Only a few feet in diameter, surface tubes are abundant at LBNM. The second type of lava tube is formed when lava flows down a pre-existing channel, such as a riverbed or a depression. The roof of the lava, exposed to air, cools and hardens forming a roof. In both cases, the supply of lava eventually ends and the lava tube drains to become a subsurface void, filled with air, water, or collapsed overburden. In addition to lava tubes, LBNM officials have located numerous "blisters" or pockets of air ranging in size from a few inches to a few feet in diameter in the subsurface at LBNM. Figure 3 shows some common lava tube features.

Geophysical Techniques

Both in theory and in practice, a variety of geophysical techniques are capable of detecting voids in the subsurface. Every technique, however, has limitations depending on site conditions and survey objectives. The physical properties of the subsurface, the estimated size and depth of the void, and the cultural features around the survey area, are determining factors when choosing appropriate techniques to map subsurface voids. Blackhawk used the following geophysical methods and equipment in an attempt to detect lava tubes:

- Ground Penetrating Radar (GPR) – Geophysical Survey Systems, Inc. (GSSI) SIR-2000 control unit using 200 and 400 MegaHertz (MHz) antennas;
- Magnetics – Geometrics G858 Magnetometer;
- Electrical Resistivity – Geometrics OhmMapper TR2;
- High Resolution Shear Wave (HRSW) consisting of;
    - Bay Geophysical patented "MicroVib";
    - 96-channel OYO DAS-1 Seismograph; and
    - 96-channel "Land Streamer" with 40-Hz OYO SMC70 horizontal geophones.

Ground Penetrating Radar

GPR is a non-invasive geophysical method utilizing electromagnetic (EM) waves to map subsurface boundaries (i.e. lithologies, utilities, debris, water table, contaminate plumes, etc.). The use of GPR is site specific and is primarily controlled by the electrical (dielectric permittivity and electrical conductivity) and magnetic (magnetic permeability) properties of the subsurface.

As the GPR system is towed along a surface, an electromagnetic wave is transmitted into the ground (Figure 4). A fraction of the wave is reflected back to the surface when it encounters a boundary where there is a change in electrical and/or magnetic properties. The propagation of EM waves follows many of the same principles as that of acoustic waves used in seismic methods.

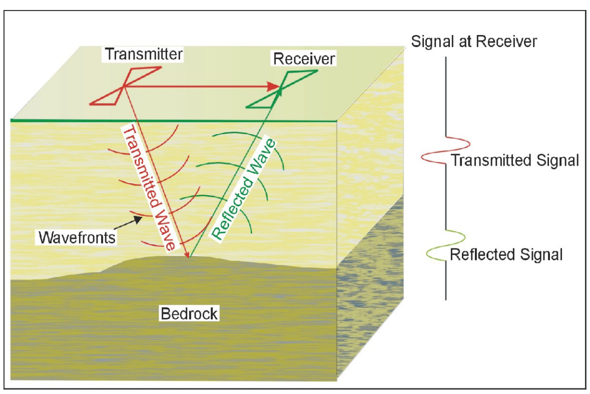

Figure 4 – The GPR method

Geometrics G858 Magnetometer

Magnetic methods have a wide range of uses in geophysical exploration. The magnetic method works by mapping variations in the magnetic field. The variations of the magnetic field can be complex due to large variations in the direction of the magnetic vectors, the changing of polarity of the earth's own magnetic field, and the effects of latitude on magnetic measurements.

The Geometrics G858 Magnetometer (G858) measures the Earth's total magnetic field (Figure 5). The total field is a summation of the anomalous fields and the background field of the earth. The remnant field is a magnetic field locked in the minerals as they cool, such as magnetite in basalt. The remnant field is orientated in the direction of the earth's magnetic field at the time of cooling. A base station, a static magnetometer, is usually set up at a fixed location to measure the earth's background field in order to account for natural variations in the background data. When the background field is subtracted from the total field, we are left with the anomalous field. The contribution to the magnetic field by earth materials usually consists of an induced field, which is related to the magnetic susceptibility of the material and the Earth's present day magnetic field, along with the remnant magnetization of the material.

The anomalous field gives the information used to identify potential survey targets. In our case, the target we are trying to locate is a subsurface void, or lava tube. Included in the anomalous field is the remnant magnetization of the basalt. Over a void, where there is a lack of basalt and therefore lack of remnant magnetization, there will be a decrease in the measured magnetic field. Depending on the orientation of the remnant magnetic field in the basalt and the orientation of the present day magnetic field, a void could appear as either a magnetic high or low in the total field magnetic data.

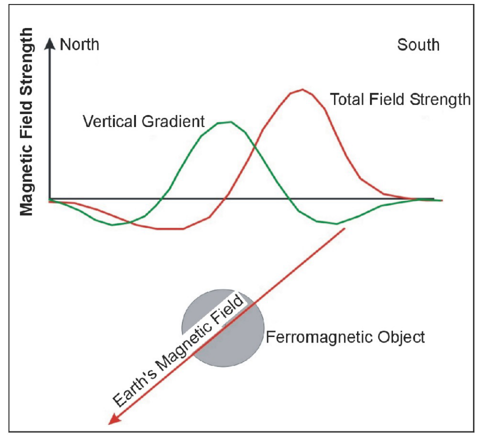

Figure 5 – The magnetic response from a ferromagnetic object

Geometrics OhmMapper TR2

Resistivity methods measure the apparent resistivity of the subsurface. In the resistivity method, current is injected into the subsurface through current electrodes. The potential difference (voltage) is measured between a pair of potential electrodes. Apparent resistivity is generally a measurement of the average resistivity of a volume of the subsurface material. The apparent resistivity is calculated by dividing the measured potential difference by the input current. Then, the answer must be multiplied by a geometric factor specific for each array to give an accurate apparent resistivity.

When the current electrodes are close to the potential electrodes, the resistivity values represent the near surface. As the distances between the current electrodes and the potential electrodes increase, the depth of investigation also increases. Depth of investigation is a function of the array type, the electrode spacing, and the input current.

The TR2 is a capacitively-coupled system designed to measure subsurface resistivities in areas with high surface resistivity. It uses an uncoupled dipole transmitter and receiver and may be used in areas where traditional galvanically coupled (DC) resistivity systems are impractical. The system utilizes two receiver electrodes and one transmitter electrode that are set up in a Dipole-Dipole configuration. As the system is pulled along the surface, the dual offset allows for the instrument to record information about multiple depths. The Dipole-Dipole array, in this situation, obtains data from multiple depths while moving laterally, thus mapping both the lateral and vertical resistivity variations of the subsurface.

High Resolution Shear Wave (HRSW)

The seismic reflection technique can be divided into two categories based on the type of seismic energy used; Compressional, or P-waves, and Shear waves, or S-waves. Compressional, or P-waves, propagate through the earth as a series of compressions and rarifications, and are identical to ordinary sound waves. Particle motion for P-waves is parallel with the direction of propagation. S-waves propagate through the earth by distorting the shape of the medium they are passing through. Particle motion in S-waves is perpendicular to the direction of wave propagation. An important feature of shear waves is that, unlike P-waves, they will not propagate through liquids or gases, as these materials have no shear strength. This makes them particularly valuable for the detection of voids, fractures, and faults.

The seismic reflection method involves projecting acoustic energy down from the surface, and then recording the acoustic energy back at the surface as it reflects off of boundaries at depth (Figure 6). A seismic reflection occurs when an acoustic wavefront encounters an impedance boundary in the subsurface. Seismic impedance depends on

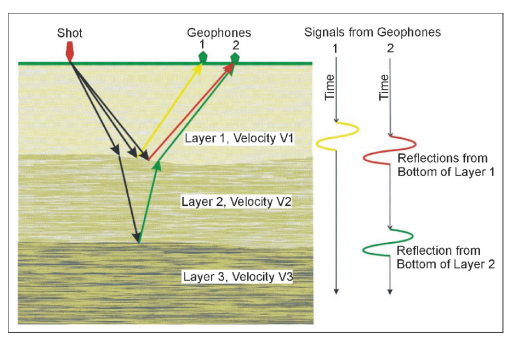

Figure 6 – The seismic method

both the velocity and density of a rock. Impedance boundaries occur where these rock properties change abruptly, usually due to changes in lithology.

Data Acquisition Procedures

Figure 7 – GPR data collection at Hercules with the 400 MHz antenna and survey wheel

GPR

Three lines of GPR data were collected over the road at four sites with the SIR-2000 system. The lines were placed four to five feet apart and were 80 to 340 feet (24 to 104 meters) in length. Fiberglass measuring tapes were laid out on every line to regulate distances. The SIR-2000 control unit was setup in the back of a vehicle, while a cable connected it to the antennas. Two (2) different frequency antennas, 200 and 400 MHz (Figure 7), were utilized at Golden Dome, Hercules Leg, Indian Well, and Monument Road Cave. A survey wheel was used for data collection at 12.2 scans per foot (40 scans per meter) at Golden Dome, Indian Well, and portions of Hercules Leg. All other GPR data were collected at 32 scans per second with user marks made in the data every 16.4 feet (5m).

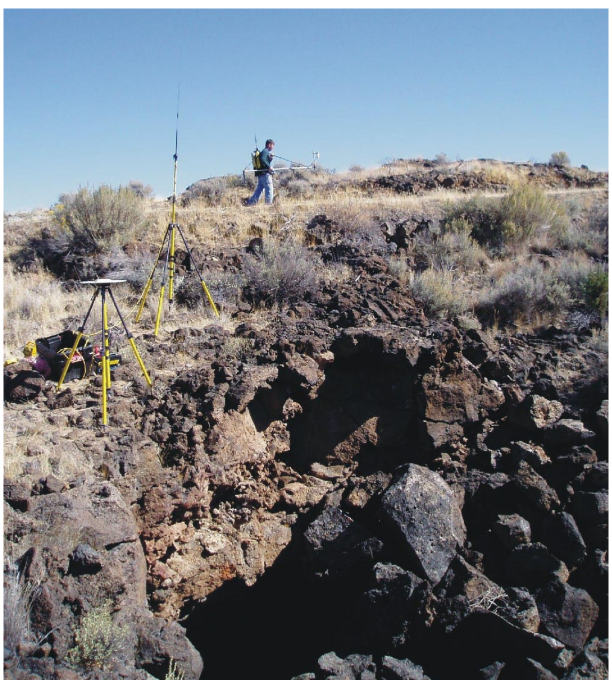

Figure 8 – Magnetic data collection at Monument Road Cave (note the DGPS base station in the foreground and backpack worn by operator)

G858

Prior to data collection, it was determined that magnetic data must detect voids in a few passes over roads in order to be both a cost and time effective method for void detection. Three lines of data using one magnetometer sensor were collected at each site for this reason. The magnetic data were collected along either side of the road and down the center of the road (approximately 5- to 7-foot line spacing) at Golden Dome, Hercules Leg, Indian Well, and Monument Cave. G858 data were recorded at 10 times per second (10 Hertz). The magnetic data were coupled with DGPS data for positioning (Figure 8). DGPS data recorded at 1 reading per second (1 Hertz). In order to diurnally correct the magnetic data, a G858 base station was established near the parking area at Indian Well Cave for data collected at Golden Dome, Hercules Leg, and Indian Well Caves. A G858 base station was established on the west side of the road at Monument Road Cave.

TR2

Data were collected with the OhmMapper TR2 along the roads at Hercules Leg, Indian Well, and Monument Cave. The TR2 array (Figure 9) consists of two receiver electrodes and one transmitter electrode. The transmitter and receivers are separated by non-conductive rope. The length of the non-conductive rope determines the depth of investigation. At LBNM, Blackhawk used two ropes with lengths of five and ten meters. The different rope lengths provide different depths of investigation. The array

Blackhawk utilized, however, had an additional dipole cable between the two receiver electrodes. The effects of this additional cable will be discussed in the interpretation.

Blackhawk started data collection in a stationary mode with the center of the non-conductive rope at a known location. The TR2 data were collected by manually towing the array at all locations, recording data at 2 Hertz with marks placed in the dataset at points marked on the road. These points, termed fiducial marks, were later surveyed with a Differential Global Positioning System (DGPS).

Figure 9 – TR2 data collection at Golden Dome Cave

HRSW

Blackhawk collected 190 foot profiles of HRSW data at Indian Well, Golden Dome and Monument caves. At these sites, the LandStreamer, consisting of 96 geophones at 2 foot intervals, was laid flat on the road in a straight line. The first geophone on the LandStreamer was designated as shot point 101, the last geophone as shot point 196. The MicroVib was then positioned adjacent to the LandStreamer and between geophones (Figure 10), in a configuration known as “shooting on the half station”. After testing the equipment and sweep parameters, data collection began at shot point 101.5 (half station between geophones 101 and 102), and carried on through shot point 195.5, with the LandStreamer remaining in a fixed position.

Data collection at the Hercules Leg lava tube was carried out in a slightly different manner in order to obtain a longer profile. The equipment was setup as before, and data collection proceeded in the manner described above until the MicroVib reached shot point 148.5. In this position, the geophones were evenly distributed around the MicroVib (48 ahead and 48 behind) in a “symmetric split spread” configuration. At this point, the MicroVib and LandStreamer were both advanced together on 2 foot intervals (the LandStreamer was pulled by a winch) for 55 shots. From this location (shot point 204.5), the LandStreamer remained stationary and the MicroVib advanced through the spread to the end. A total of 151 shots were recorded for a total line length of 300 feet.

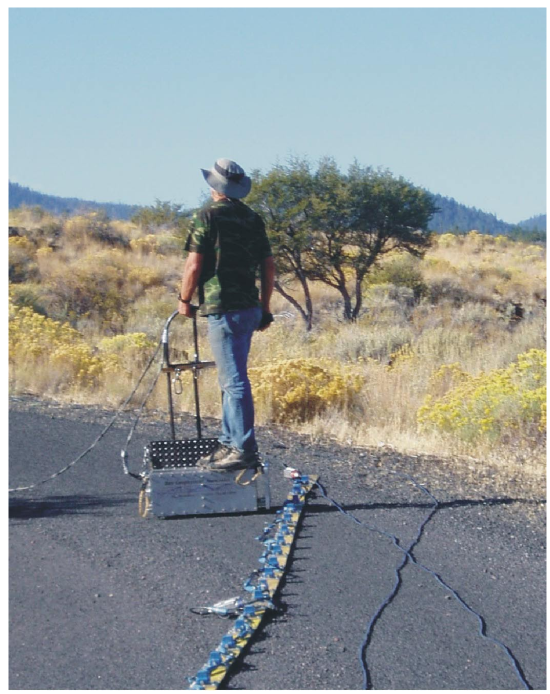

Figure 10 – The MicroVib and LandStreamer at Golden Dome

Surveying

All above ground surveying was accomplished with the Trimble 4700 Real Time Kinematic Differential Global Positioning System (DGPS). Geophysical survey points (i.e. geophone locations and survey line start and end points) as well as points of interest (i.e. cave openings, estimated cave location, and road locations) were recorded. Additionally, DGPS data were coupled with G858 data for positioning purposes.

Compass and Chain Surveying

Blackhawk field personnel used the compass and chain method to find the approximate location where the cave passed beneath the road. Additionally, Blackhawk was able to approximate both the height and the width of the cave underneath the road and the thickness of overburden between the road and the roof of the cave. The equipment utilized in the survey included a compass, measuring tape, hand-level, and stadia rod (data presented in Table 1).

Table 1 – Survey results at each location.

Cave	Overburden Thickness (feet)	Width of Cave Under Road (feet)	Height of Cave Under Road (feet)
Monument Cave	18	40	18
Indian Well Cave	29	26	27.8
Golden Dome Cave	13	12.5	8.8
Hercules Cave - North	10.7	32	2.5
Hercules Cave – South	8.7	73	8

Data Processing and Interpretation

Data were processed using the following software packages:

- GPR data were processed using GSSI's RADAN GPR processing software and displayed using Corel Draw;
- G858 data were processed using Geometrics MagMap2000 processing software and displayed using Geosoft's Oasis montage;
- TR2 data were processed using Geometrics MagMap2000 processing software and Geotomo Software's RES2DINV program and displayed using Corel Draw;
- EM31 data were processed using Geonics DAT31 processing software and displayed using Geosoft's Oasis montage;
- HRSW data were processed using UNIX-based LandMark ProMax® software and displayed using Geophysical Microcomputer Associates (GMA) software and Corel Draw.

For the purposes of this paper, selected geophysical data from select cave locations have been presented. A complete report discussing all of the locations and all of the geophysical methods is available from the Central Federal Lands Highway Division (CFLHD), FHWA, Denver, CO.

It is important to note that all locations are approximate. Due to the fact that the HRSW LandStreamer was pre-assembled, with geophones spaced two feet apart, that method is displayed in feet. In order to compare the GPR data to the seismic data, it is displayed in English units as well. All G858 positioning data are given in U.S. Survey Feet, California State Plane Zone 1.

Hercules Leg Cave

GPR Method

Processed GPR profiles are displayed with the horizontal (length) and vertical (depth) scales in feet. A relative dielectric permittivity of 8 ($\varepsilon_r = 8$) was used to calculate depth. Note the slight exaggeration in the vertical scale. The GPR profiles are displayed in a line scan format using a grayscale palette.

Voids in the subsurface will be visible in the GPR profiles in the form of reflection and/or diffraction hyperbolas (i.e. upside-down U or V shaped features in the profile). In the case of lava tube detection at LBNM, the voids will be irregularly shaped due to a highly uneven rock-void interface. This will cause the lava tubes to manifest as diffraction hyperbolas at the rock-void interface in the GPR profiles. Analyses of raw and processed profiles collected at LBNM show numerous diffractions and diffraction hyperbolas. The GPR signal is scattered by voids, fracturing, inclusions, and other inhomogeneities in the rock and provides a detailed but difficult profile to interpret. As was observed, the lava tubes are clearly evident at some locations and are obscured by numerous diffractions or depth at others. Deeper lava tubes may also be obscured in the GPR profile by other lava tubes. Multi-layer tube systems are common at LBNM.

Interpreted sections are provided with known caves highlighted in blue, and suspected caves highlighted in red. The 200 MHz antenna data has been selected for the interpretation process based upon the increase in depth of penetration and decrease in resolution, compared to the 400 MHz antenna. Based on the longer wavelength, the 200 MHz antenna data will be less susceptible to an increase in scattering than 400 MHz antenna.

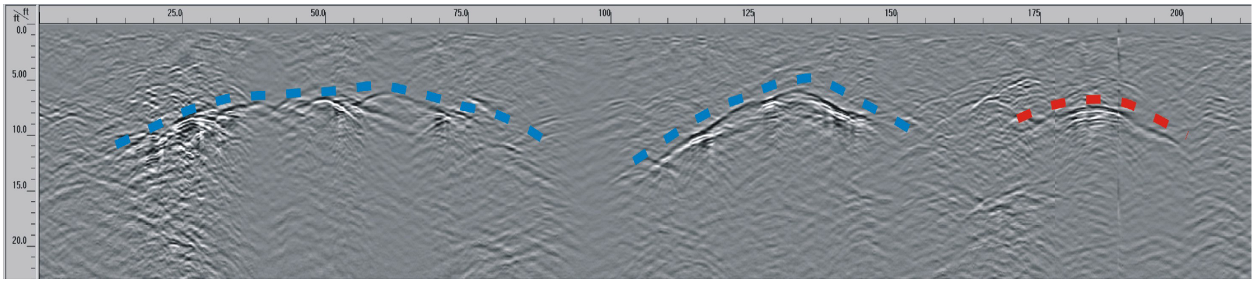

Figure 11 – GPR profile over Hercules Leg Cave (known caves are outlined in blue while an additional anomaly is outlined red)

Approximately 350 feet of data were collected along each of three profiles at Hercules Leg Cave with the 200 and 400 MHz antennas. In general all profiles correlate well with one another, between profiles and different frequency antennas, and show many of the same characteristics. The known lava tubes at Hercules Leg were the most readily identifiable lava tubes in all of the GPR profiles at LBNM. Figure 11 shows the 200 MHz data collected along Line 1 over Hercules Leg Cave. The voids are clearly evident in the processed GPR data. This is primarily due to the small amount of overburden present and possible lack of fracturing and blistering in rock in this the area.

Compass and chain surveying estimated 8.7 feet of overburden at Hercules Leg South Cave and 10.7 feet of overburden at Hercules Leg North Cave, compared to 6.5 and 6.0 feet, respectively, of interpreted overburden from the GPR Line 1 profile. Although the depths showed slight variations the estimated width of the caves appears to be more accurate. Surveying methods estimated a width of 73 feet for Hercules South and 32 feet for Hercules North. Width estimations from the GPR profiles are estimated at 70 feet for Hercules South and 40 feet for Hercules North. A third lava tube has been interpreted from the data and is displayed along with the known caves in Figure 2. This anomaly is slightly deeper, approximately 7.5 feet, and smaller in width (feet) than the two known tubes.

Under ideal conditions, GPR data may be used to determine the approximate height of a void or lava tube. However, no estimates were made from the profiles collected at LBNM.

Indian Well Cave

TR2 Method

The color scale for the resistivity figure ranges from blue for areas of low resistivity to maroon for areas of high resistivity. It is believed that the subsurface consists of mostly basalt, which has a resistivity range of approximately 200 ohm·meters to 1,000 ohm·meters. Basalt with many air-filled vesicles would have higher resistivity values. Additionally, areas with multiple fractures would also produce a higher resistivity value. A void filled with air (air is infinitely resistive) could have resistivity values from several thousands to several tens of thousands ohm·meters.

When viewing or interpreting resistivity data, it is important to understand the equivalence factor. It is possible for slightly different models to produce the same calculated resistivity values, referred to as equivalence. Although smaller features and the position of the edges of larger features may be distorted, the overall geoelectric section should remain consistent.

Figure 12 displays the data collected at Indian Well Cave in the south to north direction. The data at this site were repeatable in both directions. The background resistivity values for this site are between 1,500 ohm·meters and 5,000 ohm·meters. The peak resistivity value, 48,000 ohm·meters, of the known cave (outlined in blue) is located at 105.5 feet (32.17 meters) at a depth of 17.9 feet (5.4 meters). This depth is 10 feet (3 meters) less than the depth to the top of the cave Blackhawk calculated from the chain and compass survey. This error is due to the lack of data below 17.9 feet (5.4 meters). Since the cave appears as a half circle, with the other half of the circle below the collected data, we are unable to predict the true depth or height of the cave. The calculated width of the cave is 20 feet (6.1 meters), which is close to the surveyed width of 26 feet (7.9 meters). There are three other areas of high resistivity (> 28,000 ohm·meters) at Indian Well Cave site. All three anomalies, outlined in red, appear as half circles along the bottom edge of the graph. To identify the vertical extent of these anomalies interpreted as lava tubes, it would be necessary to survey deeper.

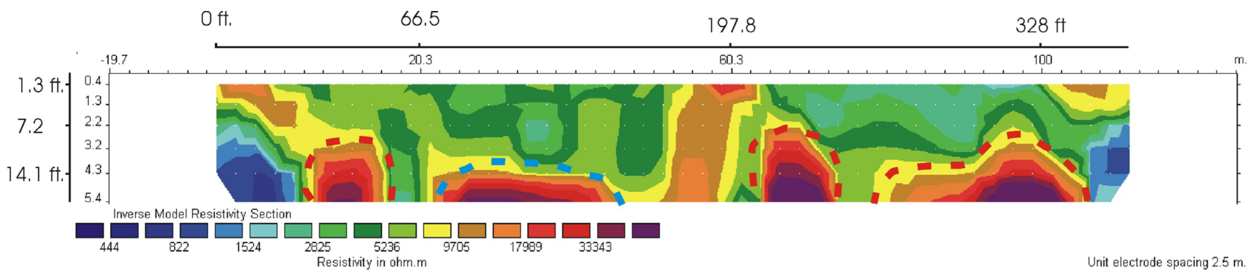

Figure 12 – TR2 profile over Indian Well Cave (known cave is outlined in blue while additional anomalies are outlined in red)

HRSW Method

HRSW data are displayed as profiles in a wiggle trace/variable area format. These sections are unmigrated, and the vertical scale is time (in milliseconds). Shot point numbers and distance (in feet) are displayed along the top of the section. The brown shading on the profiles is a derived seismic attribute known as Amplitude Envelope, calculated from the Hilbert Transform of each trace. The Amplitude Envelope display is used to enhance steeply dipping events on the seismic data. Note that for this seismic profile, 1 millisecond is roughly equivalent to 2 feet.

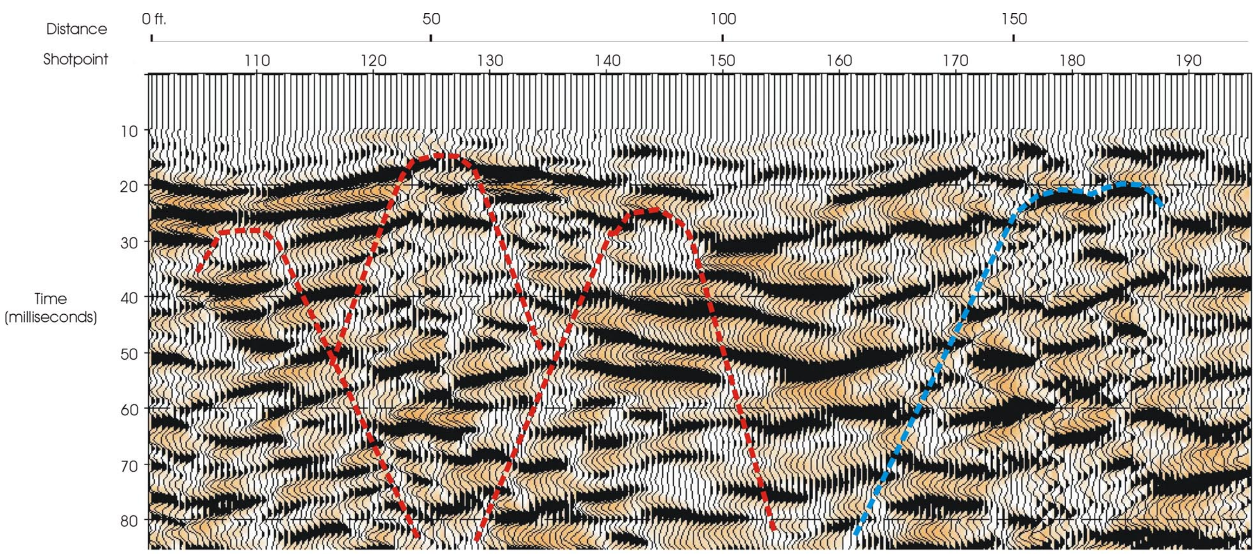

Figure 13 – HRSW profile over Indian Well Cave (known cave is outlined in blue while additional anomalies are outlined in red)(Note: the HRSW and TR2 data were collected in reverse direction and have been displayed that way)

An interpreted section is provided in Figure 13. Zero time is at an elevation of 4710 feet. The known cave beneath this profile is centered at shot point 180 and extends about 13 feet on either side of this point. The stacking velocity in the vicinity of the known cave is approximately 4450 feet/sec, and the expected overburden is approximately 29 feet thick. The reflection from the top of this lava tube should then occur 13 milliseconds below the start of data (the ground surface is at 10 milliseconds on this line). A reflection event is evident at this level, with a zone of disturbed seismic reflectors underneath it. A fairly strong diffraction, made evident by the Amplitude Envelope portion of the display, slopes down from the left (west) edge of the lava tube.

A suspected lava tube occurs at shot point 126, (outlined in red) and appears to be approximately 12 feet across. This anomaly originates about 13 feet below the ground surface, and is evidenced by an arcuate reflection event overlying a zone of low amplitudes bounded on either side by diffractions (again made visible by the Amplitude Envelope portion of the display). Two other suspected caves, outlined in red, are centered on shot points 109 and 144, respectively.

Monument Road Cave

G858

In order to better understand the results from the G858 data, Blackhawk used GM-SYS (a Gravity/Magnetic Modeling Software package written by Northwest Geophysical Associates) to forward model different hypothesis to explain the data. Figure 14 shows one result where a magnetic high is visible in the data over a void. The model that best fit the data suggests that the background basalt was cooled at a time when the Earth's magnetic field was opposite to its current position. The inclination used for the background basalt, above and surrounding the void, in the model is –67 degrees while current day inclination is approximately 67 degrees. Both basalt layers were given a magnetic susceptibility of 0.003 SI units and a remnant magnetization of 15 Amperes per meter (A/m). The remnant magnetization in the basalt lessens the total magnetic field measured with the G858 for this reason. This theory would produce magnetic highs over subsurface features such as voids and lava tubes. The model depicts a roofed type cave, which is the anticipated type of cave in this area. Figure 15 shows the G858 data collected over Monument Road Cave.

With this information in mind, other large areas of magnetic highs were selected as anomalous in the data. Highs in magnetic data are shown as bright pink on Figure 15, while lows are shown as dark blue. All magnetic data is measured in nanoTeslas (nT).

Monument Road Cave was successfully located using the magnetic method. Figure 5 displays the G858 data. A strong magnetic high (approximately 1200 nT), is evident over the known location of the cave. The magnetic anomaly crosses the road at an angle. This direction matches the orientation measured during surveying.

A second possible cave is interpreted to be 150 feet south of the known cave. This anomaly is outlined in red and has a peak reading of approximately 1500 nT, which decreases rapidly from the southwest side to the northeast side of the road. This anomaly has approximately the same orientation as the known cave.

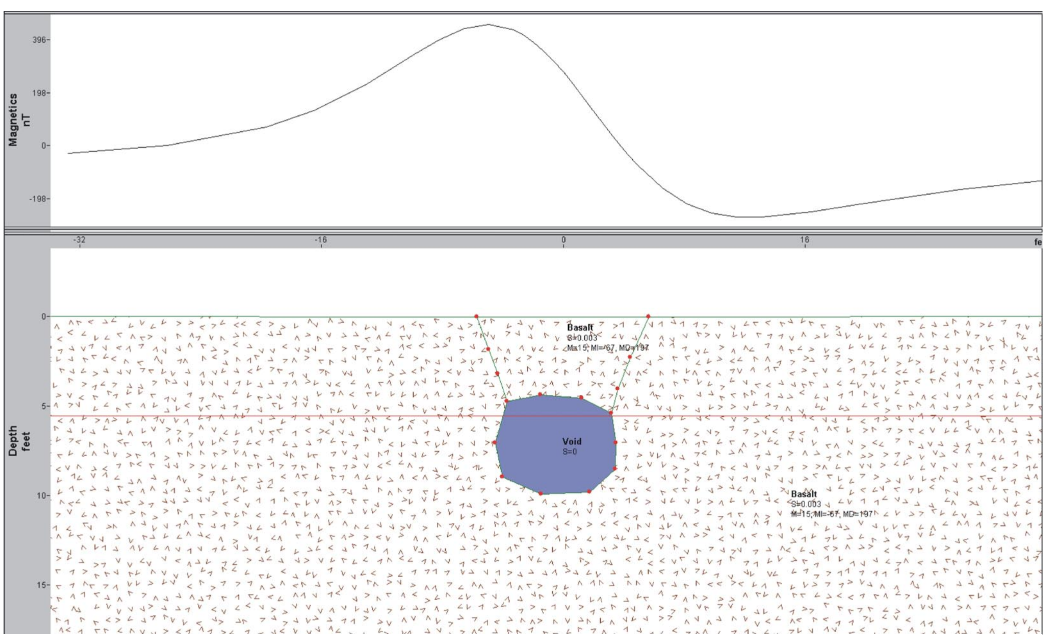

Figure 14 - Forward magnetic data model

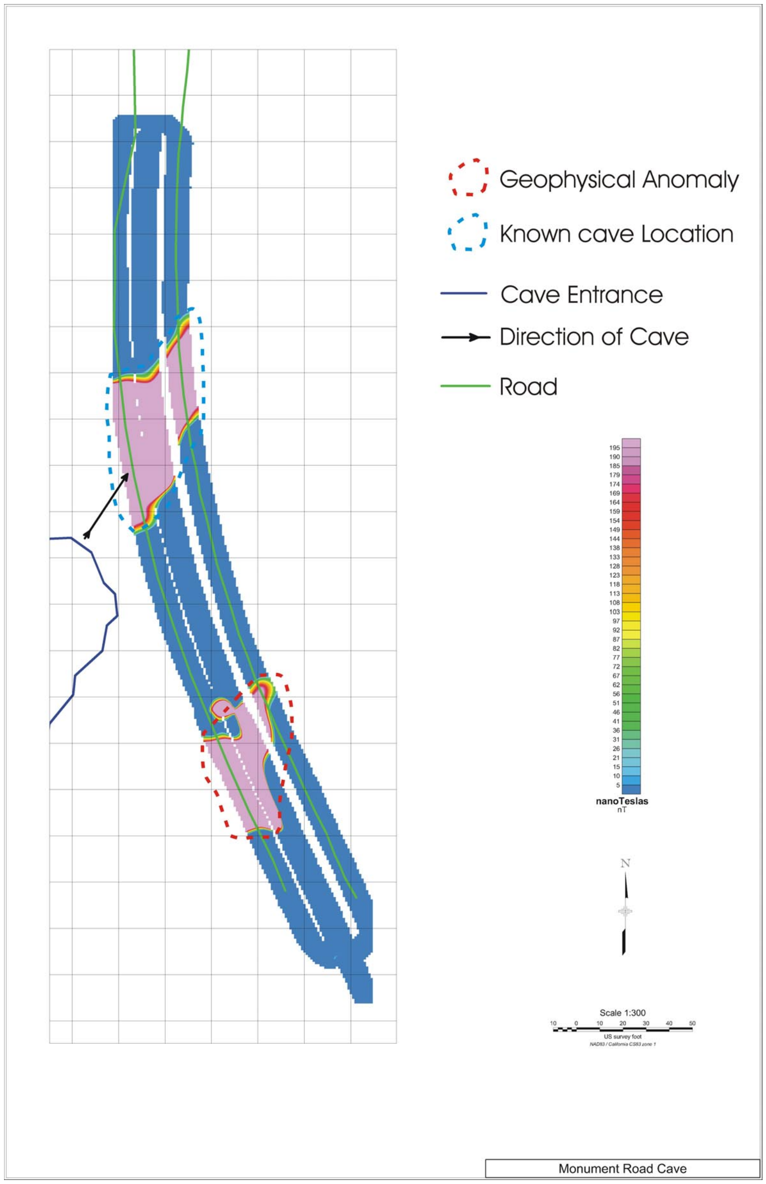

Figure 15 – Magnetic data collected over Monument Road Cave

Conclusions and Recommendations

The lava tubes profiled at Lava Beds National Monument manifest themselves in each of the geophysical methods used. However, each of the lava tube sites has unique characteristics with regard to the data collected. Although not all geophysical methods at each location were discussed in the interpretation section, they are summarized below and in Table 2:

- **Golden Dome Cave**
  - Although the GPR profiles did not cross the known cave location, there were numerous diffractions present in the data. It is unclear if the GPR method would have detected the Golden Dome Cave.
  - The known cave is readily identifiable in the G858 data near the surveyed location of the cave.

- The seismic section is dominated by reverberating reflection events, indicating the presence of shallow scoria beds in this area. An obscure reflection event occurs at the top of the cave, as well as diffractions on each side.

- **Hercules Leg Cave**
  - Each of the known caves was clearly identified in the GPR data. The depth and size were readily distinguished in either the raw or processed data.
  - Neither known cave was interpreted from the G858 data although three anomalies were identified in the data. The thin overburden present along with the height of the caves may have limited the effectiveness of the G858 method.
  - Several anomalies are present in the TR2 data, but do not have the continuity associated with them as anomalies viewed at Indian Well or Monument Road Cave. This is probably again associated with the thin overburden and size of the voids.
  - Hercules Leg Cave is wide enough under the seismic line that it traps seismic energy between the top of the cave and the surface, causing a strong reverberation down the section. Again the thin overburden present may be disguising the exact shape and size of the known voids from interpretation with this method.
- **Indian Well Cave**
  - The amount of overburden present severely limited the usefulness of the GPR method. Numerous diffractions are present in the data, but none could be attributed to the known cave.
  - A large magnetic high is visible in the G858 data at the surveyed location of the cave. The anomaly corresponds well in shape and general direction of the cave but does not give an indication of the depth and/or internal height of the cave.
  - Several anomalies, including one over the cave, are visible in the TR2 data. The anomaly over the cave is just visible at the bottom of the section. An increase in the array length (an increase in the N spacings) would be useful for future surveys to delineate large, deep voids.
  - The seismic section over the Indian Well Cave is relatively free of reverberating seismic energy, indicating an absence of shallow scoria beds. The tube can be identified by a reflection from the cave top, a diffraction from the west edge, and a zone of relatively incoherent data underneath.
- **Monument Road Cave**
  - Multiple diffractions are present in the GPR data. This cave was not directly imaged using GPR but may be visible in the data by the numerous diffractions in the overburden above it.
  - The G858 data clearly show the known cave along with approximate width and general direction. A second anomaly is present to the south and was visible in the TR2 data as well.
  - Two high resistivity anomalies are clearly evident in the TR2 data. The known cave was easily interpreted from the data as well as a second anomaly also visible in the G858 data.
  - The Monument Road Cave is evident from the arcuate reflection from the top of the cave. However, the section is composed predominantly of reverberating seismic energy, bouncing back and forth between a shallow scoria bed and the surface.

Table 2 – Final results from all geophysical surveys.

Location	Geophysical Method			
	GPR	G858	TR2	HRSW
Golden Dome Cave	NA	Y	NA	Y
Hercules Leg Cave	Y*	N	Y	Y
Indian Well Cave	N	Y	Y*	Y*
Monument Road Cave	N	Y*	Y	Y

* Locations discussed in this paper.

Overall, each known lava tube was detected with at least two geophysical methods. The large voids, Indian Well and Monument Road Cave, were easily detected with the G858 and TR2 systems. Although the lava tubes at LBNM are visible in the HRSW data sets, they would be difficult to interpret without some knowledge beforehand of their locations. For this reason, along with the ease in data acquisition, surveying with the G858 or TR2 makes them more favorable methods for data collection over long distances. These data sets may also be relatively quickly processed and interpreted. Anomalies interpreted from the G858 or TR2 data may then be investigated further using the HRSW or GPR method. The HRSW method is effective at determining depths as well as width estimates over voids thought to have more than 10 feet of overburden. Once the characteristics of a known cave can be observed in the data, then others can be interpreted using similar criterion. It is therefore recommended for future work, that shear wave reflection surveys be "calibrated" against a known cave in the local area. In turn, the GPR method was effective at detecting voids down to depths of 13 feet, without "calibration," and may be a more practical method for determining shallow void characteristics where individual anomalies are not distinguishable in either the G858 or TR2 method. Although GPR may not be effective at mapping voids with more than 13 feet of overburden, it would confirm that anomalies detected in the G858 or TR2 data would have at least 13 feet of overburden when using the 200 MHz antenna.

It is clear that the geophysical methods used at LBNM were successful at detecting lava tubes. It would be most effective to use a combination of geophysical methods to identify the location of lava tubes.

Acknowledgments

The authors would like to thank the Park Superintendent and the staff at Lava Beds National Monument for the all of their help.

References

Larson, C. and Larson, J., Lava Beds Caves, 1990, ABC Publishing.

http://www.goodearthgraphics.com/virtual_tube/virtube.html